Soil carbon stock changes in tropical croplands are mainly driven by carbon inputs: A synthesis

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ABSTRACT

Soil organic carbon (SOC) balance is an important component of the terrestrial carbon (C) budget. However, effect of cropland management changes on SOC dynamics has not been recently assessed in the tropics.

Studies were compiled in the tropics where SOC stocks were measured in the topsoil (0–20 or 0–30 cm depth) after the adoption of management practices that are expected to enhance SOC stocks, including tillage reduction, crop rotation, exogenous organic amendments, restitution of crop residues, mineral amendments, and combinations of these practices. Random forest regression was used to identify the determinants of SOC accumulation rates (ΔSOC) depending on the climate, soil characteristics and changes in management practices.

214 cases were identified in 48 studies in 13 different countries. The average ΔSOC was 0.41 ± 0.03 Mg C ha^{-1} yr^{-1} (significantly greater than zero), for an average experiment duration of 13.6 ± 0.6 years. Although a large part of the variability remained unexplained due to methodological bias in the studies or a lack of relevant predictors. The strongest predictors of ΔSOC were C inputs, duration of the experiments, and the management practices, whereas neither soil characteristics (soil type, clay content, and initial SOC stock) nor climate variables (mean annual temperature and rainfall, aridity index) affected ΔSOC. The SOC accumulation rates increased linearly with C inputs, and the conversion rate of C inputs to SOC was $8.2 \pm 0.8\%$. Given the competing uses of organic matter on many tropical farms, the benefits of using changes in management practices for climate change mitigation might be overrated. As ΔSOC decreased with the duration of the experiments, ΔSOC would probably be smaller if a period of 20 years were considered, as recommended by the IPCC guidelines. The management practice with the greatest ΔSOC was diversified crop rotation. Cropping systems where diverse practices were combined resulted in higher ΔSOC than individual practices such as reduced tillage and mineral fertilization on their own.

The adoption of improved management practices that increase C inputs is still relevant for meeting the challenges of food security and adaptation to climate change.

1. Introduction

Changes in soil use and management to increase soil organic carbon (SOC) stocks have been identified as a mean of mitigating climate change (Minasny et al., 2017; Paustian et al., 2016; Smith, 2016).Carbon (C) sequestration in the soil is the net carbon dioxide (CO$_2$) removal from the atmosphere to the soil, where C is stored in soil organic matter (Feller and Bernoux, 2008; Stockmann et al., 2013). Furthermore apart of their role in global carbon balance, soils are also a vital resource for humankind, hosting biodiversity, regulating nutrient cycles, food production, erosion, and fresh water quality (Banwart et al., 2014; Keesstra et al., 2016). There was thus a need to considerer and characterize the land managements that increase SOC stocks.

Large land-use changes, especially deforestation, have taken place in the tropics in recent years (Grace et al., 2014). As conversion of forest to cropland lead to SOC depletion (Deng et al., 2016; Don et al., 2011), there should be a significant potential for SOC accumulation in tropical croplands. Furthermore it may be appropriate to concentrate

on tropical croplands when seeking to increase SOC stocks, as this also contributes to improving food security and adapting to climate change (Paustian et al., 2016). SOC is particularly important for the fertility of tropical soils, since soil organic matter supplies most of the nutrients such as nitrogen and phosphorous taken up crops that receive little or no mineral amendments. Tropical soils are often highly weathered with a low cation exchange capacity and need the support of organic inputs such as manure or crop residues for the retention of nutrients and water (Bationo et al., 2007; Castellanos-Navarrete et al., 2015; Palm et al., 2001). Increasing SOC stocks in the tropical croplands would therefore help towards meeting the 4 per 1000 initiative targets for climate change mitigation and food security (Minasny et al., 2017).

Changes in SOC stocks are controlled by the balance between C inputs, from plant biomass and anthropogenic organic inputs, and C losses through heterotrophic catabolism (Paul, 2016). Several factors are involved in dynamics of SOC stocks when land management changes, such as climate and soil characteristics, time since the change in practice and the amount of carbon inputs (Dlamini et al., 2016; Don et al., 2011; Laganière et al., 2010; Ogle et al., 2005; Paustian et al., 1997; Virto et al., 2012). SOC stocks can be increased through several land management strategies such as afforestation (Deng and Shangguan, 2017; Laganière et al., 2010), conversion of cropland to grassland (Deng et al., 2016; Don et al., 2011), grassland rehabilitation (Chaplot et al., 2016), restoration of degraded lands (Akpa et al., 2016) but also through cropland management (Minasny et al., 2017; Paustian et al., 1997). The cropland management practices aiming to increase SOC stocks include, for example, crop diversification (Poeplau and Don, 2015), organic or mineral fertilization (Han et al., 2016; Maillard and Angers, 2014), restitution of crop residues (Turmel et al., 2015), agroforestry practices (Cardinael et al., 2017), tillage reduction (Luo et al., 2010), and combinations of these practices, e.g. for conservation agriculture (Powlson et al., 2016). Despite the worldwide growing interest in SOC accumulation, there is no recent synthesis of changes in SOC stocks in tropical croplands. Tropical croplands support various agricultural practices. A focus on the impact of their management on the potential of soil carbon accumulation is thus needed.

An overview of the changes in SOC stocks in response to changes in agricultural practices in the tropics is required to answer simple practical questions. What is the soil C accumulation potential and what are the most appropriate management practices to fulfil this potential? The objectives of the current study were: (i) to collect the existing published data sets on agricultural management practices which are expected to increase SOC stocks in tropical croplands; (ii) to evaluate the SOC accumulation rates can be expected in tropical croplands when management practices are changed and (iii) to identify the predictors of SOC accumulation rates.

Published data from field experiments on SOC accumulation after a change in the agricultural practices for tropical croplands were collected and meta-analyzed.

2. Materials and methods

2.1. Data collection

Data were collected by systematic searching of peer-reviewed literature supplemented by searches for relevant grey literature using web search engines (Google Scholar and Web of Science; 1960–2016). Keywords used were "soil organic carbon"; "sequestration"; "tropic"; "carbon stock"; "annual crops"; "croplands". Only English language search terms were used but articles or PhD dissertations in French and Portuguese were also considered. The data search was restricted to studies covering areas between the tropics or having a tropical climate according to the IPCC climate classification based on elevation; mean annual temperature and rainfall (IPCC, 2010, 2006).

Paired-plot studies that met the following criteria were selected: (i)

field studies where soils were cultivated with annual crops following a given management practice established for at least three years; (ii) SOC stocks were directly reported with means and standard deviations (or standard errors and sample sizes) or where the SOC stocks could be calculated from the measured soil bulk density and organic carbon concentrations; iii) the preferred soil depth was the upper 0–30 cm as the default value recommended in 2006 IPCC guidelines (IPCC, 2006) although studies considering the upper 0–20 cm were also included to enlarge the dataset. Studies that only investigated the top 10 or 15 cm of soil profiles to assess SOC stocks were not considered as inadequate for accounting purpose (IPCC, 2006) Some studies were rejected from the dataset, when we lacked of information: absence of replication, absence of measured bulk density data, absence of a reference situation, absence of information regarding soils characteristics, absence of specific time span data, or unclear design. Studies with unrealistic SOC stocks changes, i.e. larger than 5 Mg SOC ha^{-1} yr^{-1}, were also rejected (two paired-plot comparisons). The studies selected used either diachronic or synchronic approaches. For a diachronic approach, SOC stocks are measured on the same plot before the establishment of a management practice and at the end of the experiment. For a synchronic approach, soil samples are taken from plots under improved management systems at a known time after a change from an initial reference state and, at the same time, from adjacent soils maintained in this initial reference state and considered as controls.

The variables collected included location, mean annual rainfall, mean annual temperature, soil type and clay content, management practice, duration of the experiment, and the carbon inputs applied to the soil per year when available (Supplementary material S1). When the mean annual temperature was not provided by the authors, the WorldClim value for the site location (Hijmans et al., 2005) was used. The aridity index provided by Trabucco and Zomer (2009) calculated as the ratio between the mean annual rainfall (MAR) and the mean annual evapotranspiration (MAE) were used. For approximately half the cases (102 out of 214) there were direct estimates of annual C inputs to the soil for the improved cropping systems (expressed as Mg C ha^{-1} yr^{-1}), or the information required to calculate them, i.e. quantities and C concentrations of the dry matter applied to soil.

The soil type reported in the studies to a WRB reference soil group (IUSS Working Group WRB, 2015) based on the information given in the article was assigned for each case. Four groups of soil were defined according to the clustering proposed by the Soil Atlas of Africa (Jones et al., 2013). Group I comprised relatively homogeneous sandy or young soils with limited or poor profile development: 26 Arenosols and 59 Cambisols. Group II comprised soils with a clay-rich or argic subsoil horizon with a low base status, low activity clay (1 Acrisol), high base status, high activity clay (10 Luvisols) or high base status, low activity clay (4 Lixisols). Group III comprised soils where iron and/or aluminum chemistry plays a major role in their formation: 77 Ferralsols and 10 Nitisols. Group IV comprised soils where their properties are strongly affected by water: 22 Vertisols and 5 Gleysols. The improved management practices found in the dataset were classified according to additional features compared to the control plots or initial states: ROT for crop rotation, e.g. introduction of legumes, cover crops or annual grasses, MIN for mineral fertilization, TILL for no or reduced tillage, and ORG for organic C inputs further be categorized as EOM for soil amendment with exogenous organic matter such as manure or compost and RES for the restitution of crop residues. Management practices with applications of both mineral and organic inputs were recorded as MIN + ORG. Many combinations of these practices were found, e.g. conservation agriculture practices that combined TILL + ROT + RES practices. There was a generic classification TILL + for tillage reduction associated with other practices.

Agroforestry practices were not evaluated since too few studies of tree-based or shrub-based intercropping with annual crops (such as alley cropping) that met the selection criteria were found.

2.2. Data analysis

For each observation, the annual SOC accumulation rate, ΔSOC expressed in Mg C ha^{-1} yr^{-1}, was calculated as

$$\Delta SOC = (SOC_{final} - SOC_{initial})/t \tag{1}$$

where SOC_{final} is the SOC stock measured at the end of experiment (Mg C ha^{-1}), $SOC_{initial}$ the SOC stock measured at the beginning of the experiment or in the control plot (Mg C ha^{-1}) for an equivalent depth basis (0–20 or 0–30 cm), and t the duration of the experiment (years).

When data were available, SOC stocks expressed for an equivalent mass rather than an equivalent depth were used or calculated (Ellert and Bettany, 1995). The ΔSOC was compared between the two sampling depths of 0–20 and 0–30 cm. ΔSOC was analyzed depending on management practices, soil type, and the continuous variables collected in the dataset. The average ΔSOC values were tested for significance using the parametric Student test or the non-parametric Wilcoxon test depending on the data distribution.

Random forest regression (Breiman, 2001) was used to assess the importance of the predictor variables on the variability of ΔSOC. Random forest is a machine-learning method that builds a multitude of decision trees by randomly dividing the dataset ("bagging"). In addition, each node is split with subset of predictors (independent variables) randomly chosen. The prediction is made using all decision trees. Contrary to linear regression, a random forest analysis can deal with non-linearities and allows both continuous and categorical variables for the predictors. The *cforest function* with unbiased tree algorithms in the R party package was used, as recommended by Strobl et al. (2009) when the predictor variables are of different types. The relative importance of predictor variables in the resulting model was determined using the Mean Decrease Accuracy (MDA). MDA is defined for each variable as the difference in prediction accuracy when this variable is randomly permuted.

An analysis of variance was used to assess the variability of ΔSOC depending on management practices and soil type. As ANOVA assumptions were not fully met, the Kruskal-Wallis test with Bonferroni correction was used for the post-hos test for significant variations. All statistical analyses were carried out using R (R Core Team, 2016).

3. Results

3.1. Changes in SOC stocks under annual crops

Data from seventy-five sites reported by forty-eight studies were included in the dataset for the current study (Supplementary material S1). Most of the studies were published after 2000. Only one study was published during 1980′s and two studies were published during 1990′s. The dataset covered various climate and soil conditions in 13 countries, but most studies were in the following countries: India, Brazil, Madagascar, Niger, Zimbabwe and Mexico. It included 214 paired-plot designs that satisfied the selection criteria of calculating ΔSOC from soil C stocks in control and improved-practice plots with an equivalent depth. SOC stocks were reported for the 0–20 cm soil layer in 59% (127 out of 214) of the cases (Table 1). SOC stocks could be expressed to an equivalent soil mass in 129 cases. A synchronic approach was used for 115 cases with 55 cases studied for less than 10 years, 35 for 10–20 years and 25 for more than 20 years. A diachronic approach was used for 99 cases with 37 cases studied for less than 10 years, 35 for 10 to 20 years and 25 for more than 20 years. For the controls, the SOC stocks averaged 29.2 Mg C ha^{-1} in the topsoil, with a mean value of 25.4 Mg C ha^{-1} for 0–20 cm soil layer and 34.7 Mg C ha^{-1} for the 0–30 cm soil layer. The mean duration of the experiments was 13.6 years (Table 1). Improved management practices resulted in an increase in SOC stocks with time. Averaging the differences between initial and final SOC stocks and dividing by the study duration gave an average ΔSOC of 0.41 $\pm$ 0.03 Mg C ha^{-1} yr^{-1}, which was significantly

Table 1
SOC stocks in control plots and plots with improved management practices, duration of the experiment comparing paired plots, and ΔSOC, for each layer depth. ΔSOC is significantly higher for 0–30 cm than for 0–20 cm (Wilcoxon test, P = 0.002).

	0–20 cm	0–30 cm	Both depths
SOC stocks (Mg C ha^{-1})[a]			
Control	25.4 ± 1.3	34.7 ± 2.3	29.5 ± 1.3
Improved	29.0 ± 1.4	40.7 ± 2.3	34.0 ± 1.3
Duration (years)	12.8 ± 0.7	14.9 ± 1.0	13.6 ± 0.6
ΔSOC (Mg C ha^{-1} yr^{-1})			
Mean[a]	0.32 ± 0.03	0.54 ± 0.07*	0.41 ± 0.03
Min	−0.41	−0.25	−0.41
1st quartile	0.08	0.17	0.10
Median	0.24	0.24	0.29
3rd quartile	0.46	0.82	0.59
Max	1.83	3.50	3.50
n	127	87	214

[a] Means are followed by standard errors.

different from zero at P < 0.05. ΔSOC was highly variable ranging from −0.41 to 3.5 Mg C ha^{-1} yr^{-1} with extreme positive outliers (Table 1 & Fig. 1). Average ΔSOC was significantly higher for the 0–30 cm soil layer than for the 0–20 cm soil layer and, for both sampling depths, ΔSOC was significantly different from zero at P < 0.05 (Table 1).

The 1st and 3rd quartiles were 0.1 and 0.59 Mg C ha^{-1} yr^{-1} respectively and ΔSOC was positive in 193 cases out of 214 (90%) (Fig. 1). For 128 cases (60%), ΔSOC was between 0 and 0.5 Mg C ha^{-1} yr^{-1}, and, for 38 cases, ΔSOC greater than 0.75 Mg C ha^{-1} yr^{-1} (Fig. 1).

3.2. Predictors of SOC accumulation rates (ΔSOC)

Fig. 2 gives an overview of the variables selected to build the random forest regression model. These variables were ordered according to their predictive performance for ΔSOC. The predictors are annual C inputs, duration of the experiment, management practices, soil group, initial or control plot SOC stocks (Mg C ha^{-1}), soil clay content, and aridity index. Overall 46% of the variance was explained by the model. Annual C inputs, duration of the experiment, and management practices had the highest MDAs for predicting ΔSOC (Fig. 2). The MDAs for the other predictors (initial SOC stocks, soil type, clay content, and aridity index) were very low. Variables that do not have an effect on SOC accumulation are presented, and then variables that influence SOC accumulation are analyzed.

For the full dataset (n = 214) clustered by soil group, group IV soils, mostly Vertisols, had the largest average ΔSOC (0.66 $\pm$ 0.18 Mg C ha^{-1} yr^{-1}), but, because of the large variability, there was no significant difference in ΔSOC between soil groups (Table 2).

Fig. 3 shows the relationships between ΔSOC and the continuous variables collected in the dataset. No correlation was found between ΔSOC and the climate variables: mean annual air temperature, rainfall, and aridity index (Fig. 3a–c). The control or initial SOC stocks also had no distinguishable effect on the ΔSOC (Fig. 3d). ΔSOC was also independent of the fraction of clay in the soil (Fig. 3e; n = 214). However, for the two soil depth subsets (0–20 cm and 0–30 cm), the variability of the SOC stocks (Mg C ha^{-1}) in the soil for initial/control plots or under improved agricultural practices was partly explained by the soil clay content (Fig. 4). On the other hand, for a given depth subset, the increase of SOC stocks with improved agricultural practices did not depend on soil clay content, as slope of the SOC stock regressions in improved plots and in initial/control plots were the same (Fig. 4).

ΔSOC was correlated with the duration of the experiments and the C inputs (Fig. 3f and g). ΔSOC decreased exponentially with the duration of the experiments, which ranged from 3 to 36 years. Additionally, the
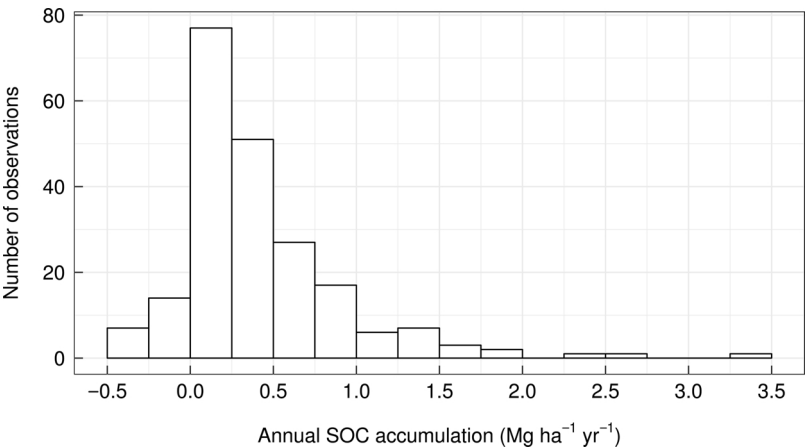
Fig. 1. Histogram of ΔSOC distribution in the full dataset (both soil depths included, n = 214).
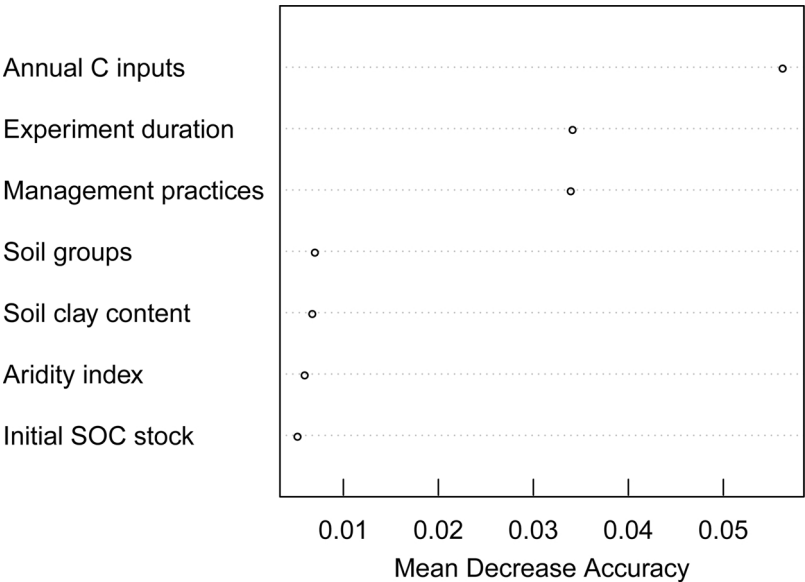

Fig. 2. MDAs for the random forest regression of ΔSOC.

variability for this relationship is higher for short-term experiments than for long-term experiments.

ΔSOC was positively correlated with C inputs ($R^2 = 0.41$, $P < 0.0001$, n = 102; Fig. 3g). The slope was 0.12 ($P < 0.0001$) and the intercept was −0.18 ($P < 0.05$) (Fig. 3). The higher ΔSOC for the 0–30 cm soil layer than for the 0–20 cm soil layer was explained by the higher C inputs for observations sampling the 0–30 cm layer (Fig. 3g).

The conversion rate of C inputs to ΔSOC was calculated as the ratio between ΔSOC and annual C inputs for the 102 cases where the C inputs were quantified (Fig. 5). The mean and median values of this conversion rate were 8.2 ± 0.8% and 6.6% respectively. There were negative rates of C input conversion for only 7 cases (Fig. 5), for various management practices (no or reduced tillage, crop rotation, mineral fertilization and/or organic inputs) of Ferralsols in Brazil (Boddey et al.,

2010; Dieckow et al., 2009) and Cambodia (Hok et al., 2015) and Luvisols in India (Manna et al. (2005), Supplementary material S1). Most of the 102 cases had positive conversion rates of C inputs, with 31 in the range 0–5%, 36 in the range 5–10%, 15 in the range 10–15%, and 13 greater than 15%. The values greater than 15% were reported by 5 studies for various soils and management practices (de Moraes Sá et al., 2015; Follett et al., 2005; Kamoni et al., 2007; Matsumoto et al., 2008; Prasad et al., 2016) (Supplementary material S1).

The results of the random forest regression (Fig. 2) show that management practices explained a significant part of the variability of ΔSOC. The highest ΔSOC values were obtained for annual crop rotation (ROT, 0.83 ± 0.17 Mg C ha^{-1} yr^{-1}) and the lowest for sole mineral fertilization (MIN, 0.24 ± 0.06 Mg C ha^{-1} yr^{-1}) and tillage reduction (TILL, 0.32 ± 0.06 Mg C ha^{-1} yr^{-1}) with a significant difference

Table 2
Topsoil ΔSOC (mean ± standard error in Mg C ha^{-1} yr^{-1}) depending on soil group. The P values testing significance of the difference of ΔSOC from zero are for the Wilcoxon test.

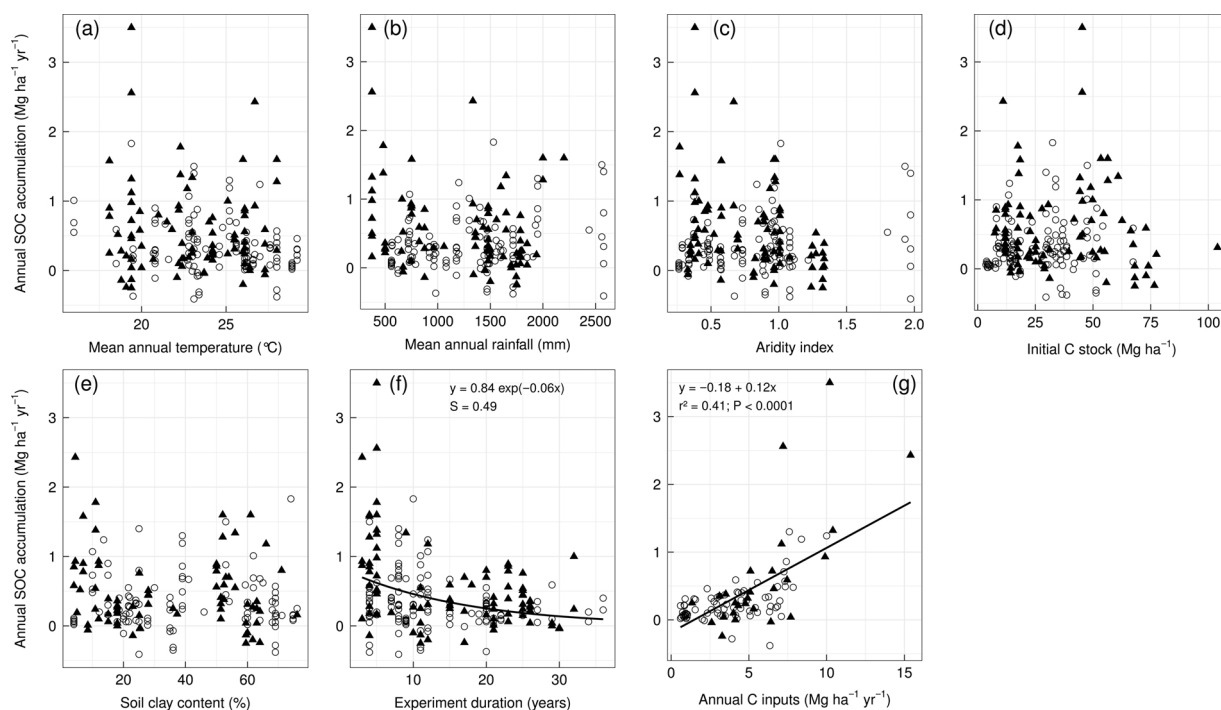| Soil group	Soil type	n	ΔSOC (Mg C ha^{-1} yr^{-1})	P value ≠ 0	Duration (Years)
I Sandy or relatively young	Arenosols & Cambisols	85	0.40 ± 0.05	< 0.0001	16.6 ± 1.0
II Clay-enriched subsoil	Acrisols, Lixisols, Luvisols	15	0.29 ± 0.07	0.0003	15.5 ± 2.6
III FeAl chemistry	Ferralsols & Nitisols	87	0.39 ± 0.05	< 0.0001	11.1 ± 0.7
IV Influenced by water	Vertisols & Gleysols	27	0.66 ± 0.18	< 0.0001	11.3 ± 1.3

Fig. 3. Relationships between ΔSOC and the continuous variables. Circles are for 0–20 cm soil depth, triangles are for 0–30 cm soil depth.
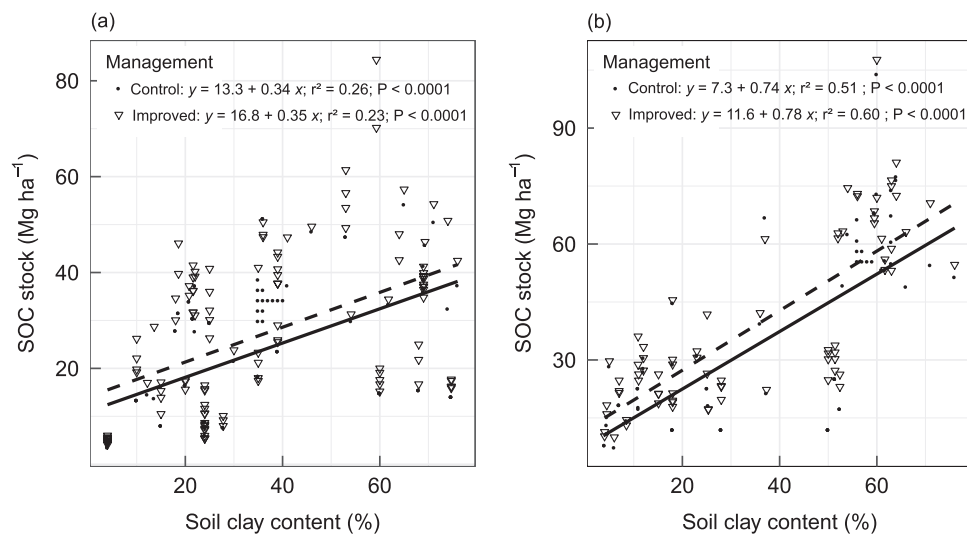

Fig. 4. Relationship between SOC stocks and clay (0–2 μm) content reported for the (a) 0–20 cm and (b) 0–30 cm layer.
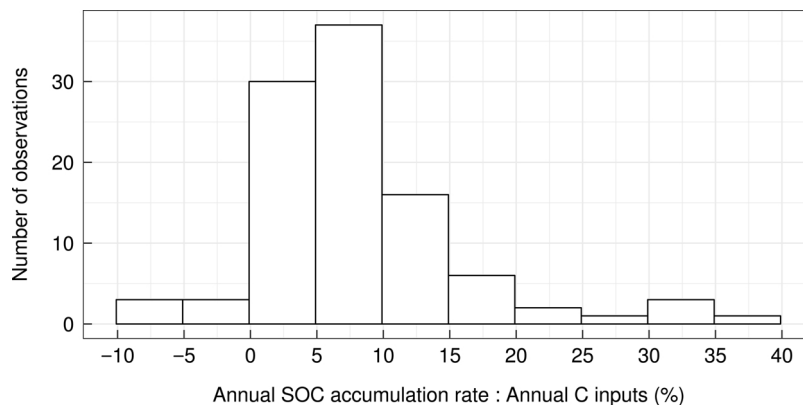

Fig. 5. Histogram of the distribution of the conversion rate of C inputs to ΔSOC, i.e. the ratio between ΔSOC and C inputs (n = 102).

Table 3
ΔSOC (Mg C ha^{-1} yr^{-1}) depending on management practices. P value $\neq$ 0 is for Student (bold numbers) or Wilcoxon tests for ΔSOC significantly different from zero, depending on the normality of the data.

Management practices[a]	n[‡]	ΔSOC (Mg C ha^{-1} yr^{-1})		Duration (Years)
		Mean $\pm$ SE[b]	P value $\neq$ 0	Mean $\pm$ SE[b]
ORG	16	0.45 $\pm$ 0.14 abc[c]	**0.0005**	**18.2 $\pm$ 1.7**
RES	*2*	*0.14 $\pm$ 0.02*	*0.0903*	*18.5 $\pm$ 3.5*
EOM	*12*	*0.51 $\pm$ 0.18*	*0.0171*	*18.7 $\pm$ 2.0*
RES + EOM	*2*	*0.43 $\pm$ 0.26*	*0.3462*	*15.0 $\pm$ 8.0*
MIN	37	0.24 $\pm$ 0.06 a	**0.0001**	17.2 $\pm$ 1.6
MIN + ORG	38	0.34 $\pm$ 0.04 abc	**< 0.0001**	22.3 $\pm$ 0.9
MIN + EOM	*27*	*0.37 $\pm$ 0.05*	*< 0.0001*	*22.6 $\pm$ 1.3*
MIN + RES	*9*	*0.31 $\pm$ 0.09*	*0.0074*	*21.7 $\pm$ 1.1*
MIN + RES + EOM	*2*	*0.16 $\pm$ 0.21*	*0.4795*	*20.5 $\pm$ 0.5*
ROT	12	0.83 $\pm$ 0.17 c	0.0005	8.1 $\pm$ 0.8
TILL	47	0.32 $\pm$ 0.06 ab	**< 0.0001**	12.3 $\pm$ 1.0
TILL+	64	0.56 $\pm$ 0.08 bc		7.3 $\pm$ 0.4
TILL + RES	*7*	*0.55 $\pm$ 0.14*	*0.0077*	*6.0 $\pm$ 2.0*
TILL + MIN	*8*	*1.22 $\pm$ 0.43*	*0.0253*	*6.5 $\pm$ 0.6*
TILL + MIN + ROT	*6*	*0.55 $\pm$ 0.22*	*0.055*	*10.0 $\pm$ 1.4*
TILL + RES + ROT	*8*	*0.78 $\pm$ 0.15*	*0.0014*	*6.4 $\pm$ 1.4*
TILL + ROT	*35*	*0.36 $\pm$ 0.08*	*< **0.0001***	*7.6 $\pm$ 0.5*

[a] ORG = any type of organic input, subdivided into crop residues (RES), exogenous organic matter (EOM) and both (RES + ORG). MIN = mineral fertilization. MIN + ORG = mineral fertilization associated with organic inputs, subdivided into EOM, RES and EOM + RES. ROT = crop rotation. TILL = reduced tillage. TILL + = reduced tillage associated with other practices.

[‡] number of cases.

[b] Standard error.

[c] Results of a Kruskal-Wallis test for the main management practices, with statistically similar clusters identified by the same lowercase letter.

between these two extremes (Table 3). Other common practices such as organic inputs (ORG), mineral plus organic fertilization (MIN + ORG) had ΔSOC values that were not significantly different from other management practices. ΔSOC for tillage reduction associated with other practices (TILL +) was significantly higher than for mineral fertilization (MIN) (P = 0.017). ΔSOC for TILL + was higher than TILL, but this difference was only significant at P = 0.062. Organic inputs (ORG) to the soil as crop residues (RES), exogenous organic matter (EOM), or both (RES + EOM) gave a ΔSOC of 0.45 Mg C ha^{-1} yr^{-1} with EOM giving the highest ΔSOC values (Table 3).

4. Discussion

4.1. Changes in SOC stocks under annual crops in the tropics

In this study, the SOC accumulation rates (ΔSOC) following agricultural land management changes ranged from -0.4 to 3.5 Mg C ha^{-1} yr^{-1} with an average of 0.41 $\pm$ 0.03 Mg C ha^{-1} yr^{-1}. The majority (60%) of the cases had a ΔSOC between 0 and 0.5 Mg C ha^{-1} yr^{-1}. This is consistent with results for conservation agriculture, comprising minimum soil disturbance, restitution of crop residues and crop diversification, giving ΔSOC values of 0.16–0.49 Mg C ha^{-1} yr^{-1} in India and 0.28–0.96 Mg C ha^{-1} yr^{-1} in sub-Saharan Africa (Powlson et al., 2016). It is also consistent with results from European trials meta-analysis, giving ΔSOC values between 0.2 Mg C ha^{-1} yr^{-1} for mineral fertilization and 0.7 Mg C ha^{-1} yr^{-1} for crop residues addition (Smith et al., 2005). This suggests that soil and climate conditions at global scale might have a modest effect on SOC accumulation rates reported in the literature.

Determining a global ΔSOC for changes in agricultural management practices in the tropics is quite challenging as the dataset is not fully representative. The ΔSOC values collected had a very large variability, and the methodology, e.g. soil samplings, bulk density or SOC content measurement, used in each study was not strictly identical. Furthermore, the fact that SOC stocks could not always be expressed for an equivalent mass rather than an equivalent depth may also introduce uncertainties in the results analysis. As for other tropical meta-analyses (Don et al., 2011; Powers et al., 2011), the geographical coverage of the dataset was

unbalanced, with few studies that met the criteria in West Africa and in humid tropics (Supplementary material S2). Although the agricultural practice changes were selected as they were expected to increase SOC stocks, in about 10% of cases ΔSOC was negative (Fig. 1). Negative values were obtained in 21 cases from 12 different studies covering various countries (Brazil, Cambodgia, India, Kenya, Zimbabwe, Senegal) and soil types (Arenosol, Cambisol, Luvisol, Ferralsol, Nitisol, Gleysol) after various improvements in management practices. These were mainly reduction of tillage alone or in combination with crop rotation, or in one case, with restitution of crop residues. For an Arenosol in Senegal and a Luvisol in India, ΔSOC was negative after application of combined mineral and organic amendments (Manna et al., 2005; Sarr, 1981). There is no evident explanation to these negative values since the lowest ΔSOC value (-0.41 Mg C ha^{-1} yr^{-1}) was from an 8 year synchronic study on a Malagasy Gleysol where the improved practice was mineral amendment of a tilled upland rice field (Razafimbelo et al., 2010), and the highest ΔSOC values (> 2.5 Mg C ha^{-1} yr^{-1}) were obtained from a 5 year diachronic study on a Mexican Vertisol where the improved practice was mineral N fertilization for no-tilled crops (Follett et al., 2005) (Supplementary material S1). Such negative values, and, more generally, the high variability in the ΔSOC values, can be explained by a high spatial variability in SOC content in some studies, especially under realistic farming conditions using synchronic approaches. It is sometimes difficult to draw meaningful comparisons of SOC stocks between different plots managed differently, where there is an inherent high variability in SOC content, for instance due to the addition of compost, mulch or crop residues, and it requires major soil sampling campaigns that are not currently common practice. This is particularly true for synchronic studies, where the errors associated with the difficulties of finding plots with the same initial soil conditions, i.e. with well-known previous land-uses and identical management history, have often led to misestimates of ΔSOC (Costa Junior et al., 2013).

ΔSOC may also depend on the soil layer considered. Although soil layers deeper than 30 cm were not considered, biomass inputs and, in particular, bi-annual rotation or crops with deep roots and high biomass production may not only increase SOC in topsoils but also in the subsoil layers (Boddey et al., 2010; Hok et al., 2015; Mathew et al., 2017). This has been also shown after land use changes from croplands to grassland or forest (Fisher et al., 1994; Stahl et al., 2016).

4.2. The determinants of ΔSOC

4.2.1. Climate variables

Climate factors, i.e. mean annual temperature, mean annual rainfall, and aridity index, did not have any effect on ΔSOC after changes in cropland management (Fig. 3). Although the effects of climate on SOC stocks is well established and is explained by the importance of water availability and temperature for biological and geochemical processes (Batjes, 2011; Jobbágy and Jackson, 2000), the effect of climate variables on SOC dynamics is still debatable. Climate has been found to have little effect in other meta-analyses dealing with changes in SOC after land-use changes or cropland management changes (Fujisaki et al., 2015; Luo et al., 2010; Virto et al., 2012). Some studies have found that climate variables affect SOC dynamics, but this may depend of the range of annual rainfall in the study. Don et al. (2011) found a negative correlation between annual rainfall and SOC after deforestation in the tropics, while Guo and Gifford (2002) found a positive correlation between annual rainfall and SOC after deforestation at global scale, but only up to 3000 mm. Larger annual rainfalls may cause topsoil erosion in agroecosystems leading to SOC depletion, but as the dataset did not include observations with annual rainfall higher than 2500 mm, this effect could not be confirmed in this study.

Climate factors may have an effect on SOC dynamics after management changes, but the covariates used in meta-analyses may be inappropriate for evaluating this effect at a global scale. The short-term pulse of SOC mineralization that accompanies the wetting of dry soils may dominate annual losses in SOC in tropical environments characterized by seasonal transitions (Miller et al., 2005). In a dry tropical ecosystem, Rohr et al. (2013) found that the SOC dynamics were affected by the length of the rainfall period rather than by the mean annual rainfall, with a non-linear pattern. For a given annual rainfall, there is an optimum wet season length for plant production, with longer wet seasons creating insufficient soil water content for plant growth, whereas short wet seasons increase runoff that also limits plant growth while increasing soil respiration. This can explain the absence of an overall effect of annual rainfall on ΔSOC in this study.

4.2.2. Soil characteristics: soil type, clay content, initial SOC stocks

Clay content and initial SOC stocks also had no effect on ΔSOC (Fig. 3). These two predictor variables were positively correlated (Fig. 4), since the relative mass of fine silts and clays is a strong determinant of SOC stabilization through the formation of organo-mineral complexes (Hassink, 1997). The SOC saturation deficit is the difference between theoretical maximum stabilized SOC and the measured SOC. As the SOC saturation deficit increases with fine particle content in cultivated soils (Feng et al., 2013; Fujisaki et al., 2018), it may be expected that clayey soils, with high initial SOC stocks, could accumulate more carbon than sandy soils. This was found in the case of afforestation (Laganière et al., 2010; Paul et al., 2002), a land use change that causes major SOC accumulation (Don et al., 2011). However, the C input levels in agricultural field experiments may be too small to show saturation behaviour (Stewart et al., 2007). Some laboratory incubation experiments have also shown that SOC accumulation in low-SOC soils was no greater than in high-SOC soils after the addition of residues (Orgill et al., 2017). In addition, the concept of saturation deficit relates to the C stabilized in the soil fine fractions and not on the total SOC. As the contribution of fine and coarse fractions to the accumulated SOC could not be assessed, it is difficult to draw any conclusions about the filling of the SOC saturation deficit in the dataset.

Soil type had no effect on ΔSOC (Table 2). Although the effect of soil properties (composition, texture, and structure) on SOC stocks has been described for the tropics (Akpa et al., 2016; Feller and Beare, 1997), SOC dynamics after land-use change do not depend on the soil type (Don et al., 2011; Feller et al., 2001). As the soil type is defined by the pedogenic horizon, it is possible that soil type is not a relevant predictor as the studies concerned the topsoil. Soils from different groups may have the same topsoil properties, e.g. Arenosols and Acrisols with a low fine-particle content. In addition, the different classification systems used in the papers reviewed (WRB, USDA, and Brazilian classification) introduce uncertainty when assigning to soil groups in a common classification system.

As well as the clay content, the Fe and Al oxide and hydroxide content in tropical soils are known to affect SOC stocks. Oxides and hydroxides are major sorbents for dissolved OM but they can also flocculate and reduce the surface area available for SOM adsorption (Six et al., 2002) or co-floculate with SOM and consequently stabilize it. Even if the processes that lead to these opposing effects are difficult to quantify, it has been shown that (i) the main factor which influences SOM contents in 18 tropical soils was the Al-containing crystalline sesquioxide content of the soil (Barthès et al., 2008) and (ii) that SOC concentration is more closely correlated with amorphous Fe and Al oxides than with other clay minerals such as kaolinite (Zinn et al., 2007). Unfortunately, the database did not allow this to be assessed as few of the studies included Al and Fe oxide data.

Unlike this study, Minasny et al. (2017) found a negative correlation between initial SOC stocks and SOC accumulation in their meta-analysis. This could be explained by the Minasny study using relative increases per year, against the absolute increases per year in this study: a small absolute increase in SOC in a soil with low initial SOC stocks would result in a large percentage increase in SOC.

4.2.3. Duration of the experiments

In this study, ΔSOC declined with the duration of the experiments (Fig. 3). The dataset combined synchronic and diachronic approaches while Costa Junior et al. (2013) reported that the diachronic approach was more accurate for the determination of soil C accumulation rates. It should be noted that the dataset mainly relied on synchronic approaches for experiments lasting less than 20 years while long-term experiments were mostly based on diachronic approaches, confirming an exponential decay relationship as the best fit for ΔSOC as a function of the duration of the improved practices. The change in SOC is a dynamic process and the rate of SOC accumulation is strongly time dependent (Franzluebbers et al., 2012; Smith, 2014; Minasny et al., 2017). A long period after a change in management practices is required for a true appreciation of the effects of management changes and to improve the understanding of the effect of management practices on SOC stocks. The default time period advised in 2006 IPCC guidelines to evaluate the effective ΔSOC for "Cropland Remaining Cropland" is 20 years (IPCC, 2006). In this study the average duration of experiments was 13.6 ± 0.6 years, therefore the ΔSOC found in this study would be reduced if duration of experiments was increased to 20 years. This highlights the need for long-term trials or surveys dealing with cropland management changes in the tropics.

4.2.4. C inputs

Results from this study confirmed that higher C inputs usually resulted in higher SOC stocks (Fig. 3). This has been extensively reported in the literature dealing with SOC dynamics in croplands after management changes (de Moraes Sá et al., 2015; Hok et al., 2015; Maillard and Angers, 2014; Virto et al., 2012). The C inputs in the dataset were the strongest predictor of SOC accumulation rates in agreement with Virto et al. (2012) who studied the effect of no tillage practices on SOC dynamics.

Although the quality of organic inputs affects ΔSOC, the quantity of organic C inputs probably has a larger effect on SOC accumulation (Gentile et al., 2010). This is particularly true when there are large C saturation deficits (Castellano et al., 2015), which seems to be the case in tropical cultivated soils. The relationship between C inputs and SOC accumulation did not show an asymptotic pattern (Fig. 3) unlike that reported by Stewart et al. (2007), suggesting that SOC saturation was not reached in the dataset of this study.

In this study, on average 8.2 ± 0.8% of C inputs were converted to

total SOC (Fig. 5) with a range from −7.3% to 35.6%. The variability of the C input to SOC conversion rate was of the same order of magnitude as that reported by Castellano et al. (2015) for field experiments, from 3% to 33%. In no-tilled soils, Hok et al. (2015) reported a C input to SOC conversion rate of 19% in Cambodia, whereas de Moraes Sá et al. (2015) found a value of ∼20.5% in Brazil.

The low C input to SOC conversion rates found in the dataset (7 cases with negative rates) are difficult to explain since no relationship between C conversion rate and the covariates in Fig. 3 was found (data not shown). However, even with improved practices, C inputs might be not large enough to maintain SOC stocks, resulting in negative SOC accumulation rates. Small amounts of crop residues, and the rapid mineralization of this biomass under optimal soil moisture conditions during the wet season, could explain why conservation agriculture systems were not always effective in increasing soil organic carbon stocks (Yemadje et al., 2017). This could explain the negative conversion rates and the low values of ΔSOC found in this study (Fig. 1). The decomposition of organic inputs is under biological control and sensitive to the decomposer communities present. The soil macrofauna, earthworms and termites, could stimulate SOC and biomass mineralization (Bernard et al., 2012) and account for the disappearance of up to half of the biomass (Manlay et al., 2004). Mineralization of native soil organic matter in response to fresh organic inputs is often referred to as a 'Priming effect' (Fontaine et al., 2007). The priming effect could also explain the negative or low ΔSOC values as overall C accumulation and loss also depend on stabilized SOM (Jobbágy and Jackson, 2000). The priming effect in tropical soil has been poorly studied at field scale, however, it seems likely that priming effects will be more significant for short term phenomena − transient increases in nutrient availability and emissions of CO_2 and other greenhouse gases (GHG) − than for long-term C sequestration (Stockmann et al., 2013). Moreover the priming effect on SOC stocks seems to depend on the nitrogen and/or phosphorus availability for the microorganisms (Bernard et al., 2012; Nottingham et al., 2015). Thus more research on the real significance of priming effects on the SOC at ecosystem, or even global, scale is needed for different soil types with different nutrient availabilities, especially in tropical environments.

4.2.5. Which annual cropping systems most increase SOC stocks?

Management practices were the third most important predictors of ΔSOC after the quantity of C inputs (Fig. 2). In the dataset, the highest levels of ΔSOC were obtained for changes of crop rotation (ROT, Table 3, ΔSOC = 0.83 ± 0.17 Mg C ha^{-1} yr^{-1}), even if the differences were significant only with respect to mineral fertilization (MIN) and tillage reduction (TILL). The benefits of adopting crop rotation, alone or with other practices, as in conservation agriculture, have already been reported in the literature (e.g. Poeplau and Don, 2015; West and Post, 2002). Most of the cases of changes in rotation in the dataset involved the introduction of grasses into the cropping system (Carvalho et al., 2014, 2010; Salton et al., 2011), which probably increased the belowground C inputs with plant root and rhizosphere inputs contributing to SOC stocks (Schmidt et al., 2011). Crop rotation can provide larger C inputs through root biomass and exudates than monoculture. The specific physical and biotic environment created by the additional plant root systems (Hinsinger et al., 2009; Jaeger et al., 1999) may also select a distinct microbial community with powerful feedback for plant growth and C cycling (Six et al., 2006). Root biomass, together with rhizodeposition is probably a major source of long-term SOC stocks as root-derived C is more likely to be stabilized in the soil by physico-chemical interactions with soil particles than aboveground inputs (Rasse et al., 2005; Schmidt et al., 2011). Although estimates of the contributions of belowground C inputs from plant root biomass to SOC are rarely measured in croplands (Denef and Six, 2006), for cereals, total root-derived C has been estimated to contribute from 1.5 times to greater than 3 times more C to SOC stocks than shoot-derived C (Allmaras et al., 2004; Balesdent and Balabane, 1996).

The analysis confirmed that mineral fertilization (MIN) was not the best management practice for increasing SOC stocks (Gentile et al., 2010; Nayak et al., 2009) although N and P deficiencies may limit SOC accumulation (van Groenigen et al., 2017). This practice resulted in the lowest ΔSOC in the dataset (0.24 ± 0.06 Mg ha^{-1} yr^{-1}, see Table 3). However, when combined with organic inputs (MIN + ORG), ΔSOC was 0.34 ± 0.04 Mg ha^{-1} yr^{-1}. Mineral fertilizer amendment is sometimes a prerequisite for crop and biomass production (Bationo et al., 2007; Vanlauwe et al., 2014) and a combination of mineral amendment and organic inputs is often considered as the key to soil fertility management in tropical soils (Bedada et al., 2016; Palm et al., 1997), not only increasing SOC stocks but also contributing to food security. Tillage reduction causes less disruption of the soil aggregate structure (Balesdent et al., 2000; Six et al., 2004) and is effective in increasing SOC stocks when it is associated with other practices such as mineral or organic amendment (TILL, ΔSOC = 0.32 ± 0.06 Mg C ha^{-1} yr^{-1} and TILL+, ΔSOC = 0.56 ± 0.08 Mg C ha^{-1} yr^{-1} respectively; P = 0.061; Table 3). For the comparisons both between MIN and MIN + ORG and between TILL and TILL +, it is likely that the higher C inputs in the combined practices explained the higher ΔSOC observed in these cases. Other studies have also shown that combined practices performed better than single practices. For example, Powlson et al. (2016) showed that ΔSOC from crop residue retention, if applied alone, was around 0.2 Mg C ha^{-1} yr^{-1} but increased to 0.45 Mg C ha^{-1} yr^{-1} when combined with no-tillage in sub-Saharan Africa.

The large variability of ΔSOC for most of the practices in the dataset confirmed that it is difficult to transfer results from a specific location to a global scale (Table 3). There are conflicting reports in the literature such as Soumare et al. (2003) who showed that mineral amendment could store more SOC than amendment with compost but Gentile et al. (2010) and Nayak et al. (2009) showed the reverse. This suggests that there is a need for long-term experiments on the effect of agricultural practices on SOC stocks and soil fertility in a variety of agroecological zones. This study provides quantitive estimate but the high variability of the soils in the dataset make it difficult to generalize the conclusions to a global scale. Moreover, some authors have argued agricultural practices for accumulating SOC should be chosen at a local scale depending on the local conditions, soil properties, availability and quality of organic matter to be applied to soil, and the socio-economic conditions affecting resource availability and economic competition with other uses for organic biomass (Bationo et al., 2007; Chivenge et al., 2011; Gentile et al., 2010; Mapfumo et al., 2007).

4.3. SOC accumulation for food security and climate change mitigation in the tropics

This study confirmed that improved management practices, especially those that increase C inputs to soil, can increase the carbon stored in the soil. This study focused on the accumulation of SOC in soils but is important to keep in mind that this is not equivalent to sequestering carbon, because carbon sequestration should consider the whole greenhouse gas (GHG) budget of a given practice (Feller and Bernoux, 2008). The N_2O emissions may be lower from tropical croplands than from temperate croplands (Hickman et al., 2014), but given the lack of data, especially in sub-Saharian Africa (Kim et al., 2016), there are still large uncertainties in the GHG budget after a management change for tropical croplands. In addition, an increase of SOC stocks is not always equivalent to a net transfer of C from atmosphere to soil, as shown by Powlson et al. (2011): for organic inputs the alternative fate of the organic matter affects the net C sequestered by the practice.

Apart from the unexplained variance, there are several other reasons to doubt that the ΔSOC values in this study could be scaled up. As shown above, C inputs were the main driver of ΔSOC. Because of the high competition for organic resources in the tropics, especially in sub-Saharan Africa (Giller et al., 2009), C inputs available to smallholders could be insufficient to raise SOC stocks. Cheesman et al. (2016)

reported that low C inputs limited the potential for SOC sequestration following conversion to conservation agriculture in farm trials in Southern Africa. Furthermore, climate change is expected to have a major effect on SOC dynamics in the future, with large SOC losses in temperate and boreal regions (Crowther et al., 2016; Meersmans et al., 2016) which may offset any increase in the C stocks due to improved management practices. However, the direction and magnitude of the effects of climate change on C stocks is uncertain in the tropics, as there is insufficient experimental data (Crowther et al., 2016).

However, apart from targeting climate change mitigation, the 4 per 1000 initiative also targets the improvement of food security through the increase of SOC stocks as do many other national and global initiatives on SOC sequestration, (Chabbi et al., 2017; Soussana et al., 2015). Enhancing food production is still the major goal in many tropical countries. Even in case of soils that cannot store large amounts of C and thus cannot contribute significantly to climate change mitigation, using exogenous organic matter in tropical croplands is essential for improving productivity and for adaptation to climate change but it may not be a priority in farm management. "Organic matter is most useful, biologically, when it decays" (Janzen, 2006) is especially true in tropical soils as the speed of mineralization of organic carbon in the form of particulate organic matter in the carbon pool is positively related to crop yields (Wood et al., 2016). Even if crop residues are not believed to be important inputs for SOC accumulation in the Sahel because of the combined effects of rapid mineralization, soil erosion caused by the arid climate, and a lack of OM protection in sandy soils (Adams et al., 2016; Janssen, 2011; Yamoah et al., 2002), crop residues could still play an important role in limiting soil acidification caused by fertilizers (Adams et al., 2016; de Ridder and van Keulen, 1990). Regular applications of manure have been shown to sustain agriculture in agro-pastoral systems (Freschet et al., 2008; Manlay et al., 2004) by supplying nutrients for the crops, N, P as well as K, Mg and Ca, increasing productivity (de Ridder and van Keulen, 1990). Furthermore, recently formed soil organic matter plays an important role in increasing yields (Janssen, 2011). High organic matter annual inputs are therefore necessary to keep SOC at an adequate level for soil fertility (10 Mg C dry matter ha^{-1} according to Janssen (2011)) and ensure the stability of yields (Chivenge et al., 2011; Pan et al., 2009) and resilience to climate change (Smith and Wollenberg, 2012). Consequently, it is vitally important to develop strategies for sustainably increasing food production in densely populated tropical areas. Where crop yields are generally very low and dependent on the organic and nutrient stocks, it is important to understand the processes which support soil productivity, such as the threshold for SOC stocks and changes, not only for climate change but, more importantly for food security. In some tropical regions the organic resources are too scarce to provide sufficient amendment for the areas that are cropped, especially in areas with high livestock feed requirements (Giller et al., 2009; Valbuena et al., 2012). The 4 per 1000 initiative, therefore, also faces the questions of where, how and what amounts of organic inputs are necessary to increase SOC stocks to improve soil fertility and productivity.

5. Conclusions

In tropical croplands, the improvement of management practices could lead to significant SOC accumulation rates. The strongest predictors of ΔSOC were C inputs, the duration of experiment, and the management practices, whereas soil and climate characteristics had no apparent effect on SOC accumulation. This result suggests that at a global scale, the efforts to increase SOC stocks should focus on those management practices that increase C inputs.

Tropical croplands may, therefore, contribute to climate change mitigation. However the competing uses of organic resources in many tropical farms makes it difficult to scale up the results of this study. In addition a large part of the variance of ΔSOC remained unexplained and more long-term trials are needed to identify the determinants of ΔSOC,

especially in regions where there is a lack of data.

Long-term trials are especially needed to identify local strategies that will increase C inputs to fields and to identify the determinants of C input conversion to SOC.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agee.2017.12.008.

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